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Development of a Single Hydraulic Fluid for Use in Army Ground Equipment

by
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A polyalphaolefin/ester-based fire resistant hydraulic fluid was developed to replace three existing military specification fluids currently used by Army equipment. The single hydraulic fluid (SHF) combines the low temperature operability exhibited by MIL-H-5606 (OHA) and MIL-H-6083 (OHT) with the fire resistance exhibited by MIL-H-46170 (FRH). SHF provides low temperature viscosities of 3500 cSt maximum at –54°C, a flash point of 180°C minimum, a minimum elastomer swell of 19% for NBR-L rubber, a maximum operating temperature of 135°C, and significantly improved corrosion protection. SHF eliminates the use of barium and tricresyl phosphate (TCP) which removes the toxic and environmental hazard restrictions of the current military specification fluids. The developmental formulations meet all performance requirements targeted for a single Army hydraulic fluid. Candidate fluids are currently being tested in armor and artillery as a final evaluation before transitioning of the fluid to the military supply system.

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Section I
Introduction

Currently, Army ground equipment uses three different military specification hydraulic fluids, MIL-H-6083 (OHT), Hydraulic Fluid, Petroleum Base, for Preservation and Operation; MIL-H-46170 (FRH), Hydraulic Fluid, Rust-Inhibited, Fire-Resistant, Synthetic Hydrocarbon Base; and MIL-H-5606 (OHA), Hydraulic Fluid, Petroleum Base, Aircraft, Missile, and Ordinance. In an effort to simplify and reduce the logistical burden of maintaining stocks of three distinct fluids, the Belvoir Research, Development, and Engineering Center (BRDEC) has developed and assessed candidate formulations for a single hydraulic fluid that can replace the three fluids mentioned above.

BACKGROUND

OHT was initiated into Army ground equipment following the Korean war in an attempt to eliminate hydraulic system corrosion problems associated with OHA. OHT is similar in chemistry to OHA except that it contains a corrosion inhibitor. Both fluids have excellent low-temperature performance properties, with OHA having a slightly lower viscosity at low temperatures than OHT. OHA has not been recommended for use in any Army ground vehicle/equipment for the past several decades, yet it is still specified in nearly 40 Army vehicle Lubrication Orders.

In the early 1970's concern arose over losses to armored tanks and crew casualties which resulted from fires partially attributed to use of the flammable OHT. As a consequence, the less flammable FRH was developed and introduced as a substitute for OHT.[1] By the mid 1970's many of the more vulnerable vehicles were converted, but some armored vehicles and self-propelled artillery remained with OHT. Typically, Lubrication Orders recommend FRH as the primary hydraulic fluid, but call for a switch to OHT for low-temperature operation. From the time of the conversion to the present, the Army has depended on three hydraulic fluids to support its ground combat and tactical equipment.[2]

Although FRH was intended to provide a significant reduction in vehicle vulnerability, several reasons have been cited for not converting completely to this fluid. First, many hydraulic systems exhibit increased sluggishness when using FRH at low temperatures as compared to the use of OHT. For some combat systems, this is considered an operational deficiency.[3,4,5] Second, there is a persistent belief that FRH is incompatible with existing seals and causes fluid leakage. Investigations into this problem have yielded inconsistent results. FRH does not swell elastomer seals to the same extent as OHT, but it does provide sufficient swell to prevent excessive leakage.[6,7]

Since none of the above fluids is acceptable for all ground vehicles/equipment in all environments, BRDEC has developed a fluid formulation that eliminates the deficiencies of the current fluids while retaining the desirable characteristics. This single hydraulic fluid will provide fire resistance comparable to FRH, and seal swell and low-temperature performance comparable to OHT. In addition, this fluid eliminates the use of barium which is considered a hazardous waste, and tricresol phosphate (TCP), the anti-wear additive which is a known neuro-toxin.

Section II
Technical Approach

Since the proposed single hydraulic fluid must remain compatible with existing hydraulic fluids and hardware, the new fluid was developed around the polyalphaolefin (PAO) and ester chemistry of the FRH.[8,9] Other constraints imposed on the fluid include a flash point of no less than 180°C, elastomer swell of not less than 19% for the standard NBR-L rubber, high-temperature viscosities comparable to FRH and low-temperature viscosities comparable to OHT. These requirements, as well as other physical, chemical and performance requirements, are shown in Table 1 for both MIL-H-46170 and SHF. Due to the physical properties of PAOs and esters, meeting all of the target requirements severely restricted the possible means of formulating an acceptable hydraulic fluid.

Table 1. Performance Requirements

PERFORMANCE TEST	MIL-L-46170	SHF
Oxidation/Corrosion ASTM D4636, #3	168 hrs @ 121°C Δvis. < 10%	168 hrs @ 135°C Δvis. < 10%
Corrosion Inhibition ASTM D1748	100 hrs	100 hrs
Galvanic Corrosion FTM 5322	10 days	10 days
Low-Temp Stability FTM 3458	72 hrs @ -54°C	72 hrs @ -54°C
Pour Point ASTM D97	-60°C	-60°C
Viscosity @ 40°C ASTM D445	19.5 cSt max	19.5 cSt max
Viscosity @ 100°C ASTM D445	3.4 cSt min	2.5 cSt min
Viscosity @ -40°C ASTM D445	2600 cSt max	800 cSt max
Viscosity @ -54°C ASTM D445	report	3500 cSt max
Solid Particle Count MIL-H-46170	10,000 max @ 5-25 micrometers	10,000 max @ 5-15 micrometers
Solid Particle Count MIL-H-46170	250 max @ 26-50 micrometers	1,000 max @ 16-25 micrometers
Solid Particle Count MIL-H-46170	50 max @ 51-100 micrometers	150 max @ 26-50 micrometers

Table 1. Performance Requirements (continued)

PERFORMANCE TEST	MIL-L-46170	SHF
Solid Particle Count MIL-H-46170	10 max @ over 100 micrometers	20 max @ 51-100 micrometers
Solid Particle Count MIL-H-46170		5 max @ over 100 micrometers
Acid Number ASTM D664	0.2 gm KOH/gm max	0.3 gm KOH/gm max
Elastomer Swell FTM 3603	15% - 25%	19% - 30%
Evaporation Loss ASTM D972	5% max	35% max
Steel on Steel Wear ASTM D4172	0.3 mm max @ 10 kg load	0.3 mm max @ 10 kg load
Steel on Steel Wear ASTM D4172	0.65 mm max @ 40 kg load	0.65 mm max @ 40 kg load
Foam Characteristics ASTM D892	65 ml max	65 ml max
Water Content ASTM D1744	500 ppm max	100 ppm max
Flash Point ASTM D92	219°C min	180°min
Fire Point ASTM D92	246° min	190°C min
Autoignition Temp ASTM E659	343°C min	325°C min
Hi Temp/Hi Press Ignt FTM 6052	no continuation of burning when ignition source is removed	no continuation of burning when ignition source is removed
Flame Propagation MIL-H-83282	0.3 cm/sec max	0.3 cm/sec max
Storage Stability FTM 3465	12 months	12 months

FRH is composed of a 4 cSt dimer-trimer PAO blend which is responsible for the high flash point of 218°C. This basestock, however, has a viscosity at -54°C of approximately 13,000 cSt, thus less viscous components were required to provide acceptable low temperature performance. The Air Force recently published a low-temperature, PAO-based hydraulic fluid specification, MIL-H-87257, Hydraulic Fluid, Fire-Resistant; Low Temperature, Synthetic Hydrocarbon Base, Aircraft and Missile. This fluid uses a predominantly 2 cSt PAO basestock and has a low-temperature viscosity of 2500 cSt maximum. The 2 cSt basestock, however, has a flash point of only 160°C.[10] Formulating with simply the 2 cSt or 4 cSt basestock requires giving up either flash point or low-temperature performance. To achieve the target performance requirements, a blend of both basestocks was required.

Other modifications to the FRH formulation involved using isodecyl esters instead of the typical diesters as the elastomer swelling agent. Diesters are commonly used for FRH because they provide satisfactory seal swell, have a high flash point, and promote increased solubility of the fluid additives. They also, however, have a significantly high viscosity at low temperatures. For this reason, other esters were considered for SHF. The isodecyl esters have low viscosities at low temperatures and, when used at treat rates of 30% - 40%, make it possible to meet low-temperature viscosity requirements.

The esters used in FRH formulations are restricted to a maximum of 30% due to their tendency to pick up water. This restriction resulted in a maximum typical seal swell of 15% - 19%. Users of FRH have reported that this is not sufficient seal swell to prevent leakage of the hydraulic fluid. SHF allows a maximum 40% ester as the swelling agent to meet the 19% - 30% swell requirement. Other formulation modifications include the substitution of tricresol phosphate anti-wear additive by a non-toxic phosphate ester, and the substitution of Barium Dinonylnaphthalene Sulfonate corrosion inhibitor by Calcium Dinonylnaphthalene Sulfonate. These substitutions were made to bring the fluid formulation in line with EPA Hazardous Waste Restrictions and to reduce the potential toxic effects of the fluid. Since the hazardous waste components and toxins have been removed from the formulations, the labeling of the containers can be altered to reflect the more benign qualities of SHF.

Section III
Results

Ten formulations were generated using the two basestocks, isodecyl ester, oxidation and corrosion inhibitors and an anti-wear agent. The viscosities and flash points obtained are shown in Table 2. Formulations for these ten fluids are contained in the Appendix.

Table 2. Viscosities and Flash/Fire Points of Candidate Fluids

FLUID	VIS @ 40°C	@ 100°C	@ -40°C	@-54°C	FLASH	FIRE
SHF 1	-	2.59 cSt	-	3445 cSt	182°C	190°C
SHF 2	8.77 cSt	2.59 cSt	668 cSt	2887 cSt	185°C	200°C
SHF 3	7.95 cSt	2.43 cSt	632 cSt	2791 cSt	181°C	193°C
SHF 4	8.79 cSt	2.57 cSt	757 cSt	3347 cSt	180°C	192°C
SHF 5	8.07 cSt	2.56 cSt	630 cSt	2979 cSt	186°C	196°C
SHF 6	9.24 cSt	2.52 cSt	806 cSt	3041 cSt	184°C	194°C
SHF 7	8.42 cSt	2.61 cSt	668 cSt	3599 cSt	178°C	189°C
SHF 8	9.12 cSt	2.56 cSt	665 cSt	3427 cSt	186°C	197°C
SHF 9	8.19 cSt	2.46 cSt	622 cSt	2934 cSt	182°C	188°C
SHF 10	8.70 cSt	2.56 cSt	636 cSt	3033 cSt	185°C	193°C

Eight of the above formulations (except SHF 3 and SHF 9) met the minimum 100°C viscosity requirement and one of those eight (SHF 7) exceeded the maximum viscosity at -54°C. SHF 7 and SHF 9 also failed to meet the flash point/fire point criteria, thus these three formulations are marginal in performance at best. Since all the formulations were so close to the required target values, all ten candidates were tested in the humidity cabinet with particular emphasis placed on those fluids meeting all viscosity requirements.

The formulations of the ten above fluids contain 1%-5% Calcium Dinonylnaphthalene Sulfonate as the corrosion inhibitor. Other formulations tested during an initial screening phase for corrosion protection incorporated 1%, 3%, or 5% Zinc Dinonylnaphthalene Sulfonate. These formulations were found to perform marginally in the humidity cabinet, failing on both sides after 88-100 hours, thus the calcium corrosion inhibitor was chosen as the desirable additive. Results of humidity cabinet testing of the candidates are summarized in Table 3.

Table 3. Humidity Cabinet Test Results

FLUID	SANDBLASTED SIDE	POLISHED SIDE
SHF 1	232 hrs	328 hrs
SHF 2	214 hrs	377 hrs
SHF 3	120 hrs	112 hrs
SHF 4	368 hrs	352 hrs
SHF 5	272 hrs	336 hrs
SHF 6	104 hrs	152 hrs
SHF 7	304 hrs	384 hrs
SHF 8	272 hrs	336 hrs
SHF 9	112 hrs	112 hrs
SHF 10	248 hrs	240 hrs

All formulations met the minimum 100 hour requirement for the humidity cabinet test. Formulations 3, 6, and 9 provided the least corrosion protection, which is to be expected as they only contained 1% corrosion inhibitor. The remaining formulations contained either 3% (SHF 2, 5, 8, 10) or 5% (SHF 1, 4, 7). A comparison of the formulations containing 3% corrosion inhibitor with those containing 5% reveals that only marginal improvement in performance is achieved with the additional 2% Calcium Dinonylnaphthalene Sulfonate. Given that the increased performance is minimal for a 2% increase in additive, there is no justification for using more than 3% corrosion inhibitor. This is especially true when the target value for SHF corrosion protection is 100 hours.

Since the decision was made to limit the amount of corrosion inhibitor to 3%, only formulations 2,5,8, and 10 were tested further. Each of these formulations were tested for galvanic corrosion protection (FTM -791-5322) with satisfactory results. Low-temperature stability was also found to be satisfactory. No signs of gelling, precipitation, or crystallization was observed after 72 hours at -54°C. There was a very slight cloudiness to the fluid which disappeared almost immediately after being removed from the cold chamber. This is not a concern, as slight cloudiness is allowed under the specification requirements for FRH, OHT, and OHA. Pour points on the fluids were tested as low as -65°C which was the lowest temperature the test apparatus could maintain. Since motion of the fluid occurred as soon as the pour point tube was tilted, the pour point of the fluid is somewhat lower than -65°C. Particle count and water content were not tested for these fluid formulations, as these property requirements can be easily met by industry when processing the fluid.

The remaining formulations were tested for their oxidation/corrosion stability in accordance with ASTM D4636, Method #3. Each of the fluids passed the criteria for metal coupon weight change and fluid viscosity change. It should be noted that MIL-H-46170 requires that the fluid be tested for 168 hours at 121°C with the same viscosity and weight change requirements. The single hydraulic fluid candidates were tested for oxidation and corrosion stability against the same criteria but at a different temperature of 135°C. Table 4 summarizes the resulting coupon weight loss for the four fluid formulations tested.

Table 4. Oxidation/Corrosion – Weight and Viscosity Change

COUPON	SHF 2	SHF 5	SHF 8	SHF 10
Cu	0.016 g	0.024 g	0.040 g	0.016 g
Al	0.032 g	0.032 g	0.040 g	0.016 g
Mg	0.008 g	0.000 g	0.064 g	0.000 g
Fe	0.072 g	0.072 g	0.088 g	0.024 g
Cd	0.176 g	0.008 g	0.104 g	0.024 g
Viscosity	4.78%	8.01%	1.66%	4.12%

As another indication of the fluid's stability, the foaming characteristics of the four candidate fluids were tested. Table 5 summarizes the results. As can be seen, each of the fluids generated only small amounts of foam and were well below the 65 ml maximum for all three testing sequences. The first number represents the maximum volume of foam generated at the end of a 5 minute aeration period, while the second number represents the amount of foam left after the fluid had been allowed to settle for 10 minutes.

Table 5. Foaming Characteristics

FLUID	SEQUENCE I	SEQUENCE II	SEQUENCE III
SHF 2	20 ml - 0 ml	20 ml - 0 ml	20 ml - 0 ml
SHF 5	5 ml - 0 ml	25 ml - 0 ml	20 ml - 0 ml
SHF 8	25 ml -0 ml	30 ml - 0 ml	20 ml - 0 ml
SHF 10	10 ml -0 ml	35 ml - 0 ml	50 ml - 0 ml

The evaporation loss of the four fluids was tested at a temperature of 149°C. As shown in Table 6, evaporation tends to be greater than 30% at this temperature. MIL-H-46170, which uses a much heavier basestock, has an evaporation of only 5%

at this temperature. MIL-H-6083, however, has an evaporation rate of up to 70% at the lower temperature of 100°C.

Table 6. Evaporation Loss

FLUID	EVAPORATION LOSS
SHF 2	30%
SHF 5	32%
SHF 8	33%
SHF 10	33%

As a laboratory indication of wear-protection capability, the four fluids were tested in the Four Ball Wear Tester at 10kg and 40kg loads. Wear criteria for single hydraulic fluid is set at the same level as that for MIL-H-46170, which is more severe than that required for MIL-H-6083 and MIL-H-5606. Table 7 reveals that all four fluid formulations tested within acceptable limits for wear scar diameter at both loads. Further wear testing will be conducted with these fluids in pump endurance tests. Results of these evaluations will be discussed in another report.

Table 7. Four Ball Wear Test

FLUID	SCAR DIAMETER @ 10KG	SCAR DIAMETER @ 40KG
SHF 2	0.25 mm	0.55 mm
SHF 5	0.21 mm	0.56 mm
SHF 8	0.24 mm	0.53 mm
SHF 10	0.24 mm	0.57 mm

The final test of the candidate formulations was the elastomer swell of NBR-L rubber for 100 hours at 70°C. Table 8 indicates that two of the formulations are just providing the minimum rubber swell required. SHF 8, which contains 34% ester resulted in the least amount of swell. SHF 5, when tested, did not yield consistent results from trial to trial. There is no explanation for this behavior, except to note that problems with consistent seal swell with NBR-L rubber are commonly experienced. For this reason, when preparing a draft military specification for single hydraulic fluid, other standard elastomers will be considered as an elastomer test material. Results of the NBR-L rubber tests, however, indicate that isodecyl ester, even at quantities above 30%, is not an ideal seal swell agent. It is the best choice for formulating SHF in that it has a high enough flash point to meet Army Safety Center requirements, without jeopardizing viscosity considerations. The fact that at least 19% seal swell is obtained indicates that the fluid formulations are acceptable for use as a single fluid replacement for the three currently in use.

Table 8. Elastomer Swell

FLUID	ELASTOMER SWELL
SHF 2	19.1%
SHF 5	-
SHF 8	16.8%
SHF 10	19.9%

Section IV
Conclusions

Through the entire testing series, four fluid formulations performed satisfactorily against the SHF target requirements. Only upon testing the formulations for elastomer swell did two formulations prove to be inadequate. Although compromises in performance were made for the SHF formulations, that which was given up is actually minor. Fire points and flash points, while lower than MIL-H-46170 do, still provide significant fire resistance and have been deemed acceptable by Army Safety. Flammability testing conducted by the Belvoir Fuels and Lubricants Facility on earlier formulations of SHF indicate a fire resistance comparable to FRH.[11] Viscosity, while not as low as MIL-H-5606, is sufficient to meet Army needs when operating at -54°C. The 2.5 cSt minimum viscosity at 100°C does not seem to have affected the wear protection of the fluid as indicated by Four Ball Wear Tests. Generally, correlation between this test and pump endurance testing indicates that the fluid should provide adequate wear protection in actual Army equipment. Finally, although evaporation loss for SHF is higher than for MIL-H-46170, since hydraulic systems are closed systems, the higher evaporation of SHF should have no effect on performance of Army equipment. As the above test results indicate, it is entirely feasible to develop a single fluid that can satisfactorily replace the three military specification fluids currently used in Army ground equipment.

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Appendix
Fluid Formulations

%	1	2	3	4	5	6	7	8	9	10
2cSt	10.8	11.2	11.2	10.4	10.8	15.5	14.5	15.0	15.0	14.5
4cSt	43.2	44.8	44.8	41.6	43.2	46.5	43.5	45.0	45.0	43.5
estr	38.0	38.0	40.0	40.0	40.0	34.0	34.0	34.0	36.0	36.0
Crln	5.0	3.0	1.0	5.0	3.0	1.0	5.0	3.0	1.0	3.0
AWr	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
AOx	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Key:

2cSt = 2 cSt polyalphaolefin basestock
4cSt = 4 cSt polyalphaolefin basestock
estr = isodecyl ester elastomer swell additive
CrIn = Calcium Dinonylnaphthalene Sulfonate
AWr = Anti-Wear Additive (non-neurotoxic phosphate ester)
AOx = Antioxidant additives (amine and phenolic)

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